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(54) **Inductively coupled plasma generator.**

(57) An inductively coupled plasma generator wherein actual power delivered to the load is measured and used to control output power. Means are provided for detecting generated RF voltage and current and multiplying these together to produce a continuous signal representative of actual RF power. Microprocessor means provides a signal representative of commanded power. These signals are compared to provide an error signal for controlling power delivered by the generator. Generator parameters are further monitored and plasma potential is maintained at zero potential with respect to ground to eliminate damage to the circuitry and instruments connected thereto.

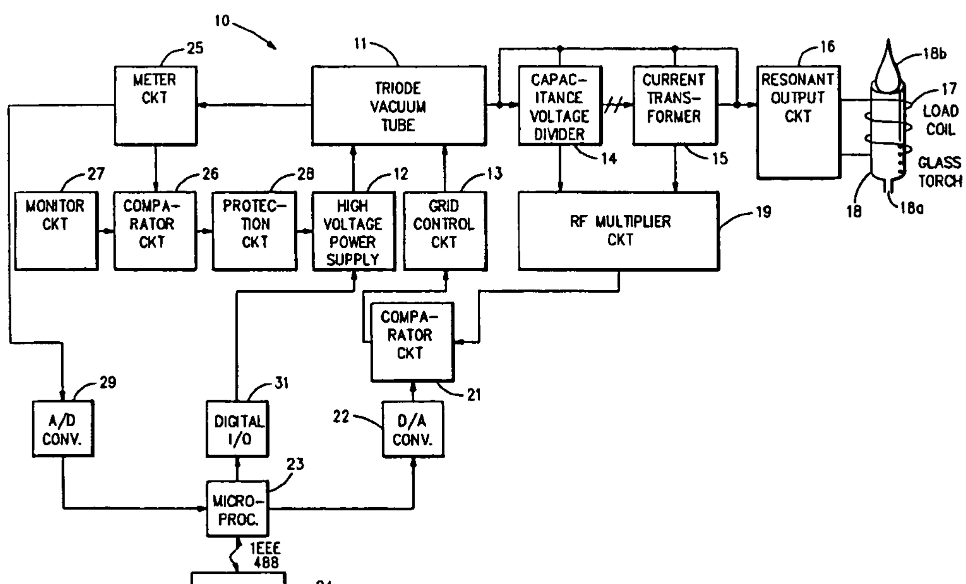

FIG.1

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BACKGROUND OF THE INVENTION

The present invention relates to plasma emission sources for use in analytical instruments such as spectrometers. Plasma emission sources provide photons and ions which are used to excite a sample to cause emission of light at wavelengths representative of the atoms of the sample. The emitted light is then detected by a spectrometer to identify the sample.

Apparatus which is used to generate or create plasma emission sources generally comprise radio frequency (RF) generators the output of which is inductively coupled to a load such as a plasma torch. Such systems are generally described in U.S. Patent. Nos. 4,629,940 and 4,935,596 issued to the inventor of the present invention.

A problem associated with all such prior systems lies in their inability to adjust and control output power adequately for use in present day systems. The present invention substantially eliminates this problem.

In such systems, the efficient transfer of power from the RF generator to the load is an important feature. Since RF generators are inductively coupled to the load, impedance mismatch between the load and RF generator is a serious problem to be overcome. This is so since impedance mismatch may result in extremely poor transfer of power as well as cause power to be reflected back which can damage or destroy the generator circuit.

In fixed frequency RF systems such as described in U.S. Patent No. 4,629,940, above mentioned, the problem of mismatch is remedied by a rather elaborate electronic-mechanical hybrid arrangement for continuously matching the impedance between the RF generator and the plasma torch or load.

The present invention solves the mismatch problem without the need of such cumbersome arrangements.

Among other innovations and improvements, the present invention eliminated the need for such elaborate and cumbersome arrangements. Since impedance and frequency are functionally interrelated, the present invention overcomes the mismatch problem by permitting the RF frequency to vary to automatically adjust for impedance mismatch. At more fully set forth in the description, a signal representative of deviation of actual RF power from desired RF power is used to control the RF generator.

Previous inductively coupled RF plasma generators were used without regard to plasma potential. Thus, in these prior systems, plasma potential may be high relative to ground which often results in destructive parasitic discharge to the glass torch in atomic emission spectrography, or erosive damage to the sampler cone in mass spectrography. The present invention overcomes this problem by maintaining the plasma at or near ground potential during operation.

The present invention also includes means for monitoring the parameters of the generator during operation and provides means for closing down operation to prevent damage to the circuitry, e.g., in inductively coupled plasma generators, non-ignition or bad ignition of the plasma can be a serious problem since such conditions may cause damage to circuitry or the glass torch. The present invention solves this problem by continuously monitoring generator perimeters to detect such ignition problems and shut down the system before damage is incurred.

SUMMARY OF THE INVENTION

The present invention relates to an inductively coupled plasma generator for generating plasma for use in analytical instruments, e.g., atomic emission or mass spectrometers. It comprises circuitry including a vacuum triode tube adapted to be used as a radio frequency oscillator for generating a plasma. The primary purpose of the present invention is the accurate adjustment and stable control of RF power to the load coil. To this end, the present invention comprises a closed loop feed back circuit wherein actual power generated is used to control oscillator output power. To accomplish this, means are provided for measuring and multiplying RF voltage and current to provide an output representative of actual RF output power. This output is compared to commanded power to produce an error signal for application to the grid of the oscillator to control its output. This is accomplished in a manner which varies efficiency of the generator as well as eliminates the need for dynamic impedance matching. The present invention also includes means for maintaining the plasma at or near zero potential as well as means for monitoring the running conditions of the generator. The condition of the plasma is continuously monitored by sensing the condition of circuit parameter in order to present damage caused by non-ignition or bad ignition of the plasma.

DESCRIPTION OF THE DRAWINGS

Fig. 1 is a block diagram illustration of the inductively coupled plasma generator present invention; and

Fig. 2 is a schematic representation of the oscillator or the present invention.

DESCRIPTION

Referring now to Fig. 1, there is shown the inductively coupled plasma generator 10 of the present invention. It comprises a triode vacuum tube 11 designed to operate as an oscillator, e.g., a Colpitts oscillator as shown in Fig. 2 in the radio frequency RF range. Plate voltage is supplied to generator 10 by means of a high voltage power supply 12. High voltage power supply 12 has the capability of supplying voltage at several discrete levels, e.g., four discrete values which correspond to low, medium, high, and ignite power ranges. Grid bias voltage is supplied to the generator 10 by means of grid control circuit 13.

Oscillator or generator 11 is connected to plasma load coil 17 which is disposed about glass torch 18. Output power to the load coil 17 is delivered via oscillator resonant circuit 16 of which load coil 17 is a part. Resonant circuit 16 is shown in schematic detail in Fig. 2. Argon or a similar gas is introduced through glass torch 18 via, e.g., an opening 18a is ionized by the electromagnetic field caused by RF power circulating through resonant output circuit 16 of which load coil 17 is the inductive part thereof. The generated plasma is symbolically shown as a flame 18b. It should be noted, however, that the plasma which comprises photons and ions is used differently depending on its use in atomic emission spectrometry or mass spectrometry.

The capacitance of the oscillator resonant circuit 16 is split as shown in Fig. 2 to act as a voltage divider to cause a virtual ground to appear at the center of load coil 17. This permits the plasma to be operated at zero or near zero potential with its attendant advantage of eliminating parasitic discharges when used in an atomic emission spectrometer and discharges that erode the orifice of the sampler when used in a mass spectrometer.

A capacitive voltage divider circuit 14 and a current transformer circuit 15 are connected between generator 11 and radio frequency multiplier circuit 19. Radio frequency multiplier circuit 19 provides an input to comparator circuit 19. Capacitive voltage divider circuit 14 provides an output representative of the RF voltage output of generator 11 to RF multiplier circuit 19 while current transformer 15 provides a signal representative of the RF current output of generator 11 to RF multiplier circuit 19. Voltage divider circuit 14 and current transformer circuit 15 are connected so as to not interfere with the RF power delivered to the load.

RF voltage and current are in effect multiplied in RF multiplier circuit 19 to give an output signal representative of the RF power actually being delivered to the plasma 18b through the load coil 17. In one embodiment of the present invention, RF multiplier circuit 19 contains identical logarithmic response amplifiers and a summation circuit similar to the AD834 four-quadrant multiplier as shown and described on page 6-65 of Analog Devices, Inc., "Linear Products Databook" 1990/91 Edition. Since the RF voltage signal and the RF current signal are logarithmically amplified and then added together, they are arithmetically equivalent to being multiplied together. Since the arithmetic product of RF voltage and RF current is RF power, the output signal from RF multiplier circuit 19 is representative of the RF power being delivered to the plasma through the load coil 17.

The signal representative of RF power is continuously applied to comparator circuit 21. A microprocessor 23 provides a second input to comparator circuit 21 indicative of desired or commanded RF power. A digital to analog converter is interposed between microprocessor 23 and comparator circuit 22 to convert the digital data from microprocessor to analog form to be compatible with the analog signal from RF multiplier circuit 19.

The comparator circuit 21 provides an error signal to grid control circuit 13. This error signal is representative of the positive or negative deviation of actual RF power going to the load coil 17 from desired or commanded power provided by microprocessor 23. This value among others is provided by a host computer having a keyboard entry system or the like and a display and/or printer. The signal from the comparator circuit 21 fed back to the grid control circuit 13 and maintains RF power to the load coil 17 constant accurately adjusted and stable at the commanded power.

Grid control circuit contains a power transistor, e.g., an FET transistor, to which the error signal is fed. The transistor controls the grid bias of triode vacuum tube 11 in accordance with the error signal.

In order to extend the range of vacuum tube 11 of an oscillator, its efficiency may be varied between approximately between 40% to 60% by varying grid current of vacuum tube 11 in accordance with actual output power, e.g., low efficiency for low grid current and high efficiency for high grid current.

A meter circuit 25 has an input from generator 11. The meter circuit 25 has an output connected to comparator circuit 26 and analog to digital converter circuit 29 which, itself, provides an input to microprocessor 23. A monitor circuit 27 provides a second input to comparator circuit 26 whose output is provided as an input to protection circuit. The output of protection circuit 28 is connected to high voltage power supply.

One purpose of this arrangement is to monitor the operating parameters of the generator 11 such

as plate voltage, plate current, and grid current. Thus, if one of the parameters exceeds a critical value set by monitor circuit 27, protective circuit 28 will cause high voltage power supply 12 to shut down. This feature is particularly important when determining the operating conditions of the plasma by monitoring grid current. Prior to ignition of the plasma discharge, grid current is extremely high. This is so since very little power is being absorbed from the load coil and most of the power provided by RF generator 11 is fed back to the grid of the generator which, as aforesaid, is essentially a triode vacuum tube. If the grid current remains high beyond a predetermined time, it may be indicative of an ignition problem. To prevent damage to the circuitry and/or glass torch 18, protective circuit 28 shuts off high voltage from power supply 12 to generator 11. Similarly, the grid current may be indicative of a good ignition by reverting from a high pre-ignition value to a stable lower running condition. Variation in grid current may also be indicative of a "bad" plasma that is one that comprises a destructive discharge. This is also detectable in time to shut off high voltage to the generator 11 before damage is incurred.

Dependent on the required RF power range, e.g., ignite or various running ranges, microprocessor 23 controls the power level output of the generator 11 by adjusting amount of power provided by the power source 12. This may be accomplished, e.g., by turning on one of four triacs or similar devices that control the level of actual high voltage to the plate of triode vacuum tube 11.

Referring more particularly to Fig. 2, there is shown the oscillator of the present invention. As can be seen, it comprises triode vacuum tube 11 connected as a somewhat modified Colpitts oscillator. Resonant output circuit 16 essentially comprises the load coil 17 connected in parallel to capacitors C_1 and C_2 whose juncture is connected to the grounded cathode. The present Colpitts oscillator circuit differs from the conventional circuit in that in the present arrangement C_1 and C_2 are made equal in value to each other and reverse connected whereas in the conventional arrangement they are not equal. In the present arrangement, the ratio of C_2 to C_3 controls grid drive power whereas in the conventional setup, the ratio of C_1 to C_2 performs this function.

By having capacitances C_1 and C_2 equal in reactances and reverse connected, the voltages across load coil 17 are equal in magnitude but opposite in phase with respect to ground. The effect of this arrangement is to produce a virtual ground at the electrical midpoint of load coil 17 which enables the plasma to operate with no indirect d.c. potential, i.e., at ground potential with the attendant advantage of eliminating damage to the glass torch in atomic emission spectrography or erosive damage to the sampler cone in mass spectrography.

The microprocessor 23 obtains information on the required or commanded RF power and other operational parameter, e.g., level of plate voltage from high voltage power supply 12 from host computer 24.

The commanded RF power signal is provided to comparator circuit 22 via digital to analog converter 22 while the high voltage (low, medium, high or ignite) at which the oscillator is to be operated is provided via to high voltage power supply 12 via digital input output circuit 31.

There has above been described an inductively coupled plasma generator which provides novel means for the accurate adjustment and stable control of RF output power. Since the circuit measures true RMS power, it takes into account the phase shift of the RF current and RF voltage due to a change in the load impedance caused by different plasma operating conditions and the tube plate impedance charge due to varying the grid bias.

In addition to maintaining the plasma at ground voltage, the grid current of the vacuum tube is constantly monitored to prevent the above-mentioned damage problems.

Finally, as aforesaid, the power adjustment range of the generator is expanded by varying the efficiency of the RF generator's vacuum tube oscillator.

Claims

1. An inductively coupled plasma generator, comprising
   oscillator means for generating RF power,
   load means connected to said oscillator for generating a plasma,
   detector means for measuring actual RF power delivered to said load means,
   circuit means connected between said load means and said oscillator means for maintaining said RF power at a commanded level.

2. An inductively coupled plasma generator in accordance with claim 1, wherein said detector means comprises
   first means connected to the output side of said oscillator means providing a voltage representative of the RF voltage output of said oscillator means,
   second means connected to the output side of said oscillator means providing a current representative of the RF current output of said oscillator means,
   third means connected to said first and

second means for effectively multiplying the outputs of said first and second means providing an output voltage representative of actual RF power delivered by said oscillator means to said inductive load means.

3. An inductively coupled plasma generator wherein said circuit means comprises
comparator circuit means connected to said third means for receiving said voltage representative of said actual RF power,
fourth means connected to said comparator circuit means for providing an input to said comparator circuit means representative of said commanded RF power,
said comparator circuit means providing an error signal output representative of the difference between said actual RF power and said commanded RF power,
control circuit means connected to said oscillator means and to said comparator circuit means for controlling the RF output power of said oscillator means in accordance with said error signal.

4. An inductively coupled plasma generator in accordance with claim 3, wherein said oscillator means comprises
a triode vacuum tube having a plate, cathode and grid.

5. An inductively coupled plasma generator in accordance with claim 4 wherein said control circuit means comprises
a grid control circuit connected to the grid of said triode vacuum tube for applying said error signal to said grid for maintaining RF output power at said commanded RF power.

6. An inductively coupled plasma generator in accordance with claim 5 wherein said grid control circuit includes
power transistor means which controls grid current to vary the efficiency of said oscillator means between limits determined by commanded RF output power.

7. An inductively coupled plasma generator in accordance with claim 6 wherein said load means comprises
a glass torch,
a load coil disposed about said glass torch,
first and second series connected capacitors connected in parallel to said load coil to form a resonant circuit therewith connected between said plate and cathode of said triode.

8. An inductively coupled plasma generator in accordance with claim 7 wherein
said capacitors are of equal value and connected at their juncture to ground whereby plasma voltage is held a zero potential.

9. An inductively coupled plasma generator in accordance with claim 8 wherein said fourth means is a microprocessor programmed to provide said commanded RF power.

10. An inductively coupled plasma generator according to claim 9 further comprising
plate voltage supply means connected between said plate of said triode vacuum tube and said microprocessor for changing plate voltage in accordance with said commanded RF power.

11. An inductively coupled plasma generator according to claim 10 wherein said first means and second means each comprise logarithmic response amplifiers and said third means comprises a summation circuit.

12. An inductively coupled plasma generator according to claim 11 further comprising
protective circuit means response to significant changes in grid current of said triode vacuum tube for disconnecting said power supply from said triode vacuum tube to prevent damage to said glass torch.

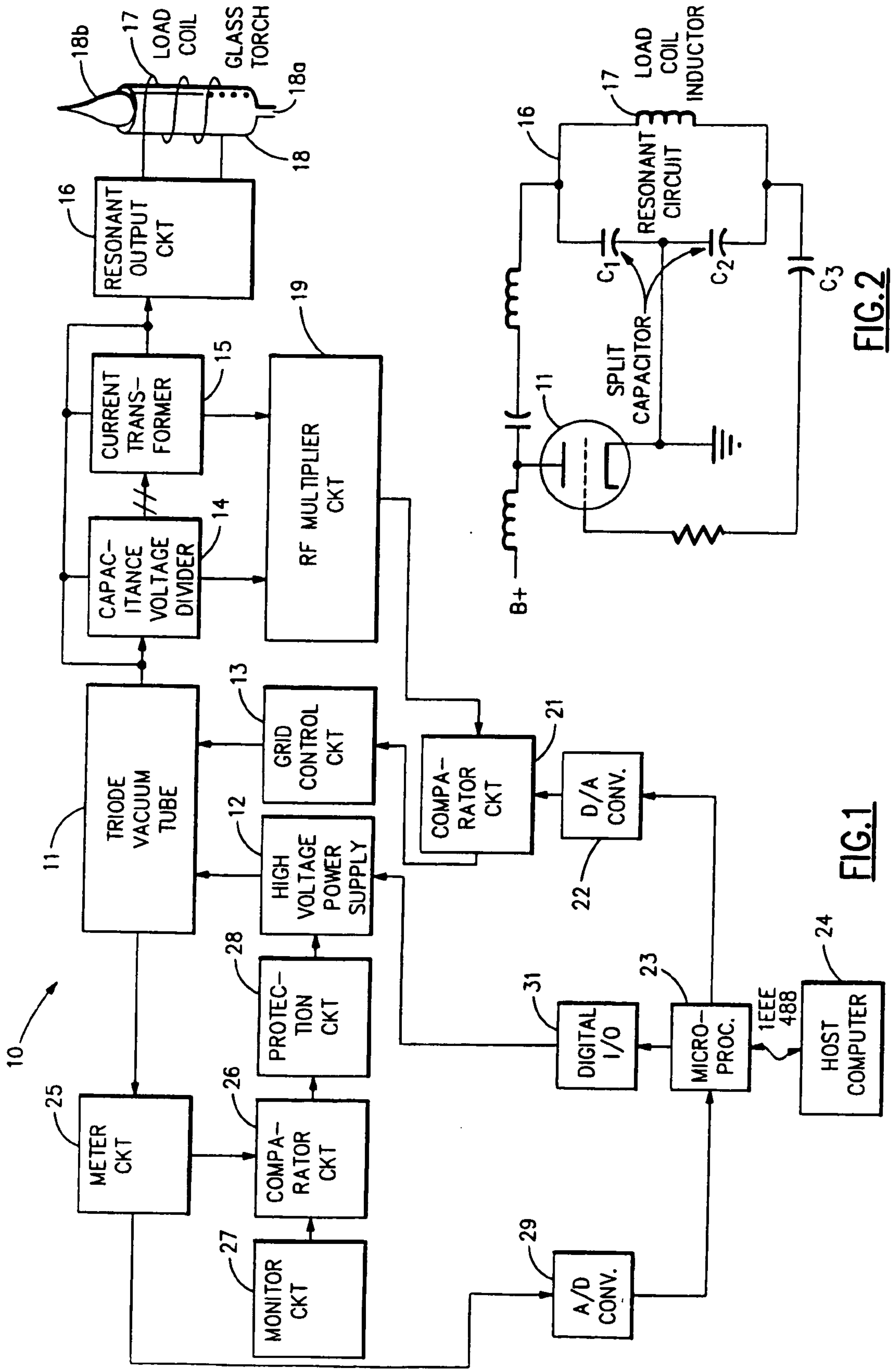
10
11
TRIODE VACUUM TUBE
12
HIGH VOLTAGE POWER SUPPLY
13
GRID CONTROL CKT
14
CAPACITANCE VOLTAGE DIVIDER
15
CURRENT TRANSFORMER
16
RESONANT OUTPUT CKT
17
LOAD COIL
GLASS TORCH
18
18a
18b
19
RF MULTIPLIER CKT
21
COMPARATOR CKT
22
D/A CONV.
23
MICRO-PROC.
1EEE 488
24
HOST COMPUTER
25
METER CKT
26
COMPARATOR CKT
27
MONITOR CKT
28
PROTECTION CKT
29
A/D CONV.
31
DIGITAL I/O
B+
11
16
17
LOAD COIL INDUCTOR
RESONANT CIRCUIT
SPLIT CAPACITOR
C_1
C_2
C_3

FIG.1

FIG.2

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EUROPEAN SEARCH REPORT

Application Number

EP 93 10 6923

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
A	PATENT ABSTRACTS OF JAPAN vol. 6, no. 169 (C-122)2 September 1982 & JP-A-57 084 743 (FUJITSU) 27 May 1982 * abstract *	1-2	H05H1/30
A	US-A-4 500 408 (BOYS ET AL.) * claims 1,4-5 *	3	
A	GB-A-1 109 602 (ALBRIGHT AND WILSON) * page 2, line 113 - line 117 * * page 4, line 63 - line 79 * * figure 2 *	1,4-5	
D,A	EP-A-0 155 496 (PERKIN-ELMER) * page 4, line 4 - line 9 * * page 5, line 7 - line 16 * * figure 2 *	7	
A	EP-A-0 281 158 (PERKIN-ELMER) * column 4, line 5 - line 23 * * column 7, line 31 - line 49 * * column 8, line 32 - line 48 * * figure 2 *	1,4,10	TECHNICAL FIELDS SEARCHED (Int. Cl.5)
A	PATENT ABSTRACTS OF JAPAN vol. 10, no. 135 (P-457)(2192) 20 May 1986 & JP-A-60 256 819 (NIPPON SHINKU GIJUTSU) 18 December 1985 * abstract *	1,3,5	H05H
A	US-A-3 909 664 (WASKIEWICZ ET AL.) * column 1, line 28 - line 61 * * column 2, line 19 - line 31 *	2-3	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	05 JULY 1993	CAPOSTAGNO E.

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
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P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document